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## Plasma Instabilities in the High and Low Latitude E-Region Induced by High Power Radio Waves

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# PLASMA INSTABILITIES IN THE HIGH AND LOW LATITUDE E-REGION INDUCED BY HIGH POWER RADIO WAVES

## 1. INTRODUCTION

The suggestion of using a ground-launched powerful high-frequency (HF) radio wave to influence (suppress or excite) naturally occurring plasma instabilities in the ionosphere was originally made by Lee et al. [1972] for the equatorial electrojet case. Similar work had been carried out later by Bujarbarua and Sen [1978] for the equatorial F-region, Stenflo [1983] for the high-latitude E-region modes, Keskinen et al. [1983] for convective modes in the high-latitude F-region, and Chaturvedi et al. [1987a] for the electrostatic ion-cyclotron (EIC) instability in the high-latitude ionosphere. These papers considered the parametric excitation of naturally occurring plasma modes by the high-frequency pump wave with the mode-coupling arising due to ponderomotive force (pmf) effects. For the collisional plasmas (such as the weakly ionized plasma of the ionosphere), it has been pointed out by many authors that the nonlinear coupling via Joule heating of electrons is an important effect and is likely to dominate over the ponderomotive force effects [Perkins, 1974; Fejer, 1979; Gurevich, 1978; Papadopoulos et al., 1983]. This latter approach has recently been incorporated in many studies such as those by Stenflo [1985] for convective modes at high-latitudes, Laxmi and Tripathi [1987] for equatorial interchange modes, and Sharma [1989] for the equatorial gradient-drift modes, among others. Chaturvedi and Ossakow [in preparation, 1989] have also included these effects in the analysis of convective fluid modes in the high-latitude ionosphere. In this report, we consider the effects of an HF pump on the E-region plasma modes, applicable to the high- and low-latitudes.

There have been many experiments using an HF pump to study its effect on the high-latitude E-region [Stubbe and Kopka, 1983; Hibberd et al., 1983; Coster et al., 1985; Djuth et al., 1985; Hoeg et al., 1986; Schlegel et al., 1987; Wagner et al., 1990, among others]. The observations indicate that a number of physical effects probably occur at different times (depending apparently on ambient conditions and also on the pump wave characteristics). On several occasions, in the above mentioned experiments, the observed effects (primarily irregularity observations) could be attributed to a presence and/or generation of naturally occurring plasma instabilities in the high-latitude E-region.

In this paper, we extend the equatorial electrojet work of Lee et al. [1972] to the high-latitude E-region case. As mentioned earlier, the nonlinear Joule heating of electrons is the dominant coupling mechanism in most situations. An important difference in the study of this region from the equatorial case is the possibility of a variety of naturally occurring plasma modes possible at the auroral latitudes. In addition to the two-stream and gradient-drift instabilities associated with the electrojet (lower E-region) and common to the low and high-latitudes, at high-latitudes, modes driven by parallel currents (at upper E-region altitudes) (ion acoustic, ion-cyclotron and current convective instabilities) should also be considered. Thus, the observed effects in an artificial ionospheric modification (AIM) experiment by HF heating at high latitudes are likely to be more variable than those in a similar experiment at the lower latitudes. We discuss the results in the context of the ionospheric modification (heating) experiments in the discussion section. The theory of parametric excitation of E-region modes by an HF pump is presented in the next (second) section, the lower and upper E-region modes are discussed in the third and fourth sections. The results are discussed in the fifth section and a summary is given in the sixth section.

## 2. THEORY

We consider the interaction of the HF pump wave with the low-frequency plasma modes (and high frequency sidebands) using the two-fluid equations. The coordinate system for the high-latitude E-region geometry is chosen so that the earth's magnetic field is aligned with the  $z$ -axis (vertical), the cross-field Hall current (carried by an equilibrium electron Hall drift,  $v_{d\perp}$ ) is along the  $y$ -axis (east-west), and the equilibrium density gradient is along the  $x$ -axis (north-south). The parallel return currents,  $J_{o\parallel}$ , are represented by an equilibrium parallel drift,  $v_{d\parallel}$  of thermal electrons. The low latitude geometry is obtained by rotating the  $zx$ -plane by  $90^\circ$  around the  $y$ -axis so that the  $z$ -axis (horizontal) points towards geographical north and the  $x$ -axis (vertical) is pointing downwards. The two-fluid equations are [Braginskii, 1965]

$$\frac{\partial n_{\alpha}}{\partial t} + \nabla \cdot (n_{\alpha} \underline{v}_{\alpha}) = 0 \quad (1)$$

$$m_{\alpha} n_{\alpha} \left( \frac{\partial}{\partial t} + \underline{v}_{\alpha} \cdot \nabla \right) \underline{v}_{\alpha} = - \nabla p_{\alpha} + e_{\alpha} n_{\alpha} \left( \underline{E} + \frac{\underline{v}_{\alpha} \times \underline{B}}{c} \right) - m_{\alpha} n_{\alpha} \underline{v}_{\alpha} \underline{v}_{\alpha} \quad (2)$$

$$\frac{3}{2} n_{\alpha} \left( \frac{\partial}{\partial t} + \underline{v}_{\alpha} \cdot \nabla \right) T_{\alpha} + p_{\alpha} \nabla \cdot \underline{v}_{\alpha} = - \nabla \cdot \underline{q}_{\alpha} + Q_{\alpha} \quad (3)$$

where  $e_{\alpha} \equiv \pm e$ ;  $\alpha \equiv e, i$ ;  $p = nT$ ;  $Q_e = (-\sum_s Q_s - \underline{R} \cdot \underline{u})$

$$\underline{u} = (\underline{v}_e - \underline{v}_i) ; s \equiv n, i ; Q_s = n_s \theta_s (T_e - T_s) ;$$

$$\theta_s = 3 \frac{m_e}{m_s} \nu_{es} ; \underline{R} = m_e n_e \underline{v}_e \underline{u}$$

In the above, most of the symbols have their standard meanings:  $n$ ,  $m$ ,  $v$ ,  $p$ ,  $T$ ,  $\nu$  are respectively the density, mass, velocity, pressure (scalar), temperature (expressed in energy units) and collision frequency of the species  $\alpha$  where the subscript  $\alpha$  is used for ions ( $i$ ) and electrons ( $e$ ). The plasma is singly ionized ( $Z = 1$ ) and thus the equilibrium electron plasma density ( $n_{oe}$ ) and ion plasma density ( $n_{oi}$ ) are assumed equal and represented by  $n_o$  ( $n_{oe} = n_{oi} = n_o$ ).  $Q$  is the heat generation term and  $\underline{q}$  is the heat flux vector. The electron collision frequency ( $\nu_e$ ) in the E-region is dominantly the electron-neutral collision frequency ( $\nu_{en}$ ) as the  $e$ - $i$  collisions are not important in this region ( $\nu_{en} > \nu_{ei}$ ). Thus in the electron energy balance equation, the dominant contribution to the heat generation term ( $Q_e$ ) comes from the  $e$ - $n$  collisions. Further,  $\theta_n = 3m_e/m_n \nu_{en}$  is the inverse of the energy relaxation time for the elastic collisions. In this work, we do not consider the contributions in the electron energy-balance equation coming from the inelastic collisions, for simplicity, though these could be of importance in the E-region [Perkins and Roble, 1978]. The above equations are supplemented by the equations for fields,

$$\nabla \times \underline{E} = -\frac{1}{c} \frac{\partial \underline{B}}{\partial t}; \quad \nabla \times \underline{B} = \frac{4\pi}{c} \underline{J} + \frac{1}{c} \frac{\partial \underline{E}}{\partial t}; \quad \nabla \cdot \underline{E} = 4\pi e(n_i - n_e) \quad (4)$$

In the analysis below, we have neglected the temperature effects and the ambient magnetic field ( $B_0$ ) effects on the high frequency modes. Both of these approximations are made for simplicity and are straightforward to include in the analysis. As a consequence of these approximations, the high frequency modes in our treatment are electron plasma oscillations, and, the pump wave frequency ( $\omega_0$ ) is chosen so as to be near the local electron plasma frequency ( $\omega_{pe}$ ). In the E-region ionosphere, the electron plasma frequency is larger than the electron cyclotron frequency ( $\Omega_e$ ). [For normal conditions, for  $n_e \gtrsim 10^5 \text{ cm}^{-3}$ ,  $\omega_{pe}/\Omega_e \gtrsim 2$  while during the periods of magnetic activity, this ratio may be larger at high latitudes e.g., the  $n_e \sim 10^6 \text{ cm}^{-3}$ ,  $\omega_{pe}/\Omega_e \sim 6$ .] Thus, the neglect of magnetic field effects on HF modes is not a good approximation under the normal E-region conditions. In the realistic situation, with magnetic field effects included, the pump wave is reflected at an altitude where the pump wave frequency matches the local upper-hybrid frequency,  $\omega_{UH}$  (where  $\omega_{UH}^2 = \omega_{pe}^2 + \Omega_e^2$ , for a collisionless cold plasma), rather than at the higher altitude where,  $\omega_0 \sim \omega_{pe}$ , as has been assumed in our treatment. In reality, the reflection occurs even at a somewhat lower altitude due to dispersive effects. A systematic study of the inclusion of magnetic field effects on the parametric instability processes has been carried out by Weatherall et al. [1981]. Weatherall et al. [1981] have shown that the inclusion of magnetic field effects leads to nonlinear frequency shifts that affect the unstable wavenumber spectra. Our analysis below focusses primarily on the possibility of artificial excitation of the low frequency modes, natural to the ambient ionosphere, in the presence of a powerful HF-pump wave, and, on the approximate comparative threshold conditions required for the excitations of these modes in different regions of the E-region. Thus, the omission of the above effects ( $T_0 = 0$ ,  $B_0 = 0$  for HF modes) may not alter importantly the conclusions on the relative threshold estimates and instability conditions for the various modes discussed below. We intend to include these effects in a future study. In the reflection region, the electromagnetic pump wave may undergo a resonant mode conversion into an electrostatic mode [Piliya, 1967]. In the analysis below, we have assumed

an electrostatic pump. The pump wave  $(\omega_0, k_0)$  is given by

$$\underline{E}_0 = E_0 \sin(\underline{k}_0 \cdot \underline{r} - \omega_0 t) \quad (5a)$$

$$\underline{v}_{eo} = -2 \bar{v}_{eo} \cos(\underline{k}_0 \cdot \underline{r} - \omega_0 t); \bar{v}_{eo} = \omega_0 e E_0 / m_e (\omega_0^2 + v_e^2) \quad (5b)$$

$$v_{eo} = v_{eo}^* = -\bar{v}_{eo}; \frac{\bar{n}_0}{n_0} = -2 \frac{k_0}{\omega_0} \bar{v}_{eo} \cos(\underline{k}_0 \cdot \underline{r} - \omega_0 t) \quad (5c)$$

where  $n_0$  is the undisturbed ambient ionospheric plasma density and  $\bar{n}_0$  is the equilibrium density fluctuation associated with the HF electrostatic pump wave. The pump wave induced oscillatory electron velocity  $\underline{v}_{eo}$  is often referred to as the "quiver velocity". The interaction of the pump with the low frequency perturbations  $(\omega, \underline{k})$  generates high-frequency sidebands  $(\omega \pm \omega_0, \underline{k} \pm \underline{k}_0)$ , with  $\omega \ll \omega_0$ . The HF sidebands are assumed electrostatic and are described by

$$v_{eH} = -i \frac{e E_H}{m_e (\omega_H + i \nu_e)} \approx \frac{i e \nabla \phi_H}{m_e (\omega_H + i \nu_e)} \quad (6a)$$

$$\nabla^2 \phi_H = 4 \pi e \tilde{n}_{eH} \quad (6b)$$

$$\frac{\partial n_{eH}}{\partial t} + \nabla \cdot (n_0 \underline{v}_{eH}) = - \nabla \cdot (n_{eL} \underline{v}_{eo} + \bar{n}_0 \underline{v}_{eL}) \quad (6c)$$

where subscript H refers to HF. In (6c), the terms on the right are the nonlinear terms. The low-frequency modes considered in this paper satisfy the inequality,  $\omega \ll \omega_{pi}$ , and as a consequence quasi-neutrality is assumed for the low-frequency modes, i.e.,

$$\tilde{n}_{eL} \approx \tilde{n}_{iL} \quad (7)$$



The ions are unaffected by the HF pump and are described by

$$\tilde{v}_i = \frac{\tilde{v}_i e E_{\perp}}{m_i (\tilde{v}_i^2 + \Omega_i^2)} + \frac{\Omega_i e E_{\perp} \hat{x} e_z}{m_i (\tilde{v}_i^2 + \Omega_i^2)} + \frac{e E_{\parallel}}{m_i \tilde{v}_i} \quad (8a)$$

$$\tilde{v}_i = v_i - i \tilde{\omega}_i; \quad \tilde{\omega}_i = \omega - k \cdot v_{id} \quad (8b)$$

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i v_i) = 0 \quad (8c)$$

The magnetic field effects on ions are retained in the above as they assume importance at higher altitudes. The ion temperature effects have been neglected in eqs. (8) for simplicity and  $v_{id}$  is the equilibrium ion drift velocity. The electron dynamics on the slower time scale is described by

$$v_{eL} = \frac{v_t^2}{\Omega_e} \left( \frac{\nabla n_{eL}}{n_o} + \frac{\nabla T_{eL}}{T_{eo}} - \nabla \psi_L \right) \times \hat{e}_z - D_{\perp} \left( \frac{\nabla n_{eL}}{n_o} + \frac{\nabla T_{eL}}{T_{eo}} - \nabla \psi_L \right) \quad (9a)$$

$$v_{e\parallel} = - \frac{v_t^2}{v_e} \nabla_{\parallel} \left( \frac{n_{eL}}{n_o} + \frac{T_{eL}}{T_{eo}} - \psi_L \right) \quad (9b)$$

$$\frac{n_{eL}}{n_o} = \frac{-i \nabla \cdot v_{eL}}{\tilde{\omega}_{eL}} - \frac{i v_{eL} \cdot \nabla n}{\tilde{\omega}_{eL}} \quad (9c)$$

$$\frac{3}{2} n_o \left( \frac{\partial}{\partial t} + v_e \cdot \nabla \right) T_{eL} + n_o T_o \nabla \cdot v_{eL} = - \nabla \cdot q_e + Q_e + [Q_e]_{NL} \quad (9d)$$

$$[Q_e]_{NL} = 2 m_e v_e n_o [v_{eHm} \cdot v_{eHn}]_{LF} \quad (9e)$$

where  $v_t^2 = (T_e / m_e)$ ;  $\psi_L = (e\phi_L / T_{eo})$ ;  $D_{\perp} = (v_e v_t^2 / \Omega_e^2)$ ;

$$\tilde{\omega}_{\alpha L} = (\omega_L - k_L \cdot v_{\alpha d}); \quad q_e = \kappa \nabla T_e; \quad \kappa_{\perp} = (c_{\chi_{\perp}} v_e n_e v_t^2 / \Omega_e^2); \quad (9f)$$

$$\kappa_{||} = (c_{\chi_{||}} n_e v_t^2 / v_e); \quad \epsilon_n^{-1} \equiv L_N = (n_o / \frac{dn_o}{dx})$$

In (9), subscript L refers to the low-frequency, and, it has been assumed that  $v_e \ll \Omega_e$  and  $v_{en} \gg v_{ei}$ . Also in the above,  $\tilde{q}$  is the heat flow vector,  $\kappa$  is the thermal conductivity and  $c_{\chi}$  is the coefficient of thermal conductivity. The perpendicular and parallel components of quantities with respect to the magnetic field are denoted by subscripts  $\perp$  and  $||$  respectively. The nonlinear heat generation term  $[Q]_{NL}$  in (9d) for electrons arises as a result of the resistive electron heating under the action of high frequency fields  $(m,n)$  (eq. 9e) where  $(m,n)$  represent the interacting modes. We are considering a four-wave process in which the high-frequency modes are the pump wave and the two side-bands and the fourth mode is a low frequency mode.

The standard mode coupling analysis is followed in the derivation of the dispersion relation. We note here that the nonlinear ponderomotive force effects have been neglected in (9) as they are usually smaller than the nonlinear thermal coupling effects in collisional plasmas if the inequality,  $v_e \gg |\omega_L|$ , is satisfied [see e.g., Papadopoulos et al., 1983]. This is the case for the low-frequency modes considered in this work. In the following, we present results of the stability analysis for different modes.

### 3. LOWER E-REGION MODES

We first consider the well known instabilities associated with the equilibrium Hall current (Lee et al., [1972]). These are likely to occur predominantly in the 100-115 km altitude range. In this region magnetic field effects on the ion dynamics may be ignored ( $v_{in} \gg \Omega_i$ ).

### (1) Two-Stream Instability (TSI)

This instability, also known as the Farley-Buneman instability (FBI), occurs when the equilibrium electron Hall drift,  $v_{dl}$ , exceeds the ion sound velocity [Farley, 1963; Buneman, 1963]. This instability is discussed in the auroral and equatorial E-region as possibly the cause of the irregularities associated with the type I VHF backscatter radar echoes [see e.g., Schlegel and St.-Maurice, 1983; Farley and Balsley, 1973]. We first give the equation describing the two-stream instability when the ponderomotive force effects were included but the nonlinear Joule heating effects were omitted [Lee et al., 1972], i.e.,

$$\tilde{\omega}_L + \alpha \omega_L + i (D_{\perp\perp} k_{\perp}^2 - \frac{v_e}{\Omega_e \Omega_i} \tilde{\omega}_L^2) = -i \frac{2 v_e k_{\perp}^2 |v_o|^2 \omega_{pe}^2 \delta}{\Omega_e^2 (\delta^2 + v_e^2 \omega_o^2)} \quad (10)$$

$$\text{where } \delta = \omega_o^2 - \omega_{pe}^2 \quad (10a)$$

From (10), it is readily observed that the pump destabilizes (stabilizes) the two-stream modes when  $\delta < 0$ ,  $\omega_o < \omega_{pe}$  ( $\delta > 0$ ,  $\omega_o > \omega_{pe}$ ). The pump power threshold to influence the two-stream modes is  $\sim 1 \text{ mW/m}^2$  and the pump electric field threshold is  $\sim 0.2 \text{ V/m}$ . The above criterion for instability and the threshold estimates are similar to the case of the equatorial electrojet considered by Lee et al. [1972]. The high latitude E-region parameters used in making the above estimate are,  $v_e \sim 4 \times 10^4 \text{ sec}^{-1}$ ;  $v_i \sim 2.5 \times 10^3 \text{ sec}^{-1}$ ;  $v_{dl} \sim 3.5 \times 10^4 \text{ cm sec}^{-1}$ ;  $\lambda \sim 3\text{m}$ . As has been noted before, the consideration of ponderomotive force nonlinearity and neglect of the thermal nonlinearity is appropriate for situations when  $|\omega_L| > v_e$ . In the case of the two-stream instability, though, the opposite is true and thus the dominant nonlinear coupling is provided by the nonlinear electron Joule heating effects, in which case, the two-stream instability is described by

$$\tilde{\omega}_L + \alpha \omega_L + i (\bar{D}_{\perp} k_{\perp}^2 - \frac{v_e}{\Omega_e \Omega_i} \omega_L^2) = \frac{8}{3} \frac{\tilde{v}_e^2 k_{\perp}^2 |\tilde{v}_o|^2 \omega_p^2 \delta}{\tilde{\omega}_{eL} (\delta^2 + v_e^2 \omega_o^2)} (1 - i \frac{2}{3} \frac{\theta_n}{\tilde{\omega}_{eL}}) \quad (11)$$

$$\text{where } \bar{D}_{\perp} = \frac{5}{3} D_{\perp}; \alpha = (v_e v_i / \Omega_e \Omega_i); \tilde{v}_{\alpha} = (v_{\alpha} / \Omega_{\alpha}) \quad (11a)$$

In the case of the two-stream modes,  $\theta_n < |\tilde{\omega}_{eL}|$  and  $\tilde{\omega}_{eL} < 0$ . The pump destabilizes (stabilizes) the two-stream instability for  $\delta < 0$ ,  $\omega_o < \omega_{pe}$  ( $\delta > 0$ ,  $\omega_o > \omega_{pe}$ ). The threshold pump electric field (power) to influence the two-stream modes when the nonlinear Joule heating effects are dominant (for the above mentioned parameters) is  $\sim 60$  mV/m ( $\sim 5 \mu W/m^2$ ). We find that the threshold values of pump power (electric field) to influence the two-stream mode are significantly lower in the case when the nonlinear Joule heating effects are dominant (eq. 11) than the case when the nonlinear ponderomotive force effect are important (eq. 10). The scale sizes generated by the two-stream instability approach  $\sim$  a few meters (which is close to the ion mean free path,  $\lambda_i < \text{meter}$ ). For these wavelengths, the ion kinetic equation should be used to include ion Landau-damping effects. The fluid equation approach appears to give reliable estimates for wavelengths larger than  $\lambda_i$  (for  $\lambda_i > 2m$ ). The above discussion also holds for most part to the low-latitude situations. At low latitudes, the electrojet peak altitude is  $\sim 105$  km (in contrast to the high latitude situation where it is  $\sim 110$  km). The peak value of electron drift at low latitudes generally exceeds the local ion-sound speed nominally but not too greatly ( $c_s < v_{dl}^{\text{peak}} < 2c_s$ ); whereas, at high latitudes,  $v_{dl}^{\text{peak}}$  may at times exceed  $c_s$  several times over.

We have shown above that in the presence of an HF pump wave of strength  $5 \mu W/m^2$  (pump electric field 60 mV/m), the two-stream modes in the E-region (at altitudes near 110 km for high-latitudes and near 105 km for low latitudes) may be excited for sub-threshold Hall drifts ( $v_{dl} < c_s$ ) in the overdense region ( $\omega_o < \omega_{pe}$ ). It was found that the nonlinear Joule heating is the dominant coupling mechanism for these modes in the E-region ionosphere (as compared with the ponderomotive force nonlinearity).

## (2) Gradient Drift Instability (GDI)

This instability occurs when the electron Hall drifts are sub-sonic ( $v_{d\perp} < c_s$ ) in the presence of an equilibrium transverse density gradient (which for instability should be in the same sense as the primary polarization electric field responsible for the electron Hall drift) [Simon, 1963; Hoh, 1963]. The gradient-drift instability favors relatively longer scale size irregularities,  $\sim 100$ 's meters in the E-region [Rogister and D'Angelo, 1970]. A two-step theory proposed by Sudan et al. [1973] for the equatorial case has been frequently invoked to interpret the type II E-region VHF backscatter echoes at the high latitudes also [Greenwald, 1974; Schlegel and St.-Maurice, 1983]. In the two-step theory, the large scale size irregularities generated by the gradient-drift instability grow to large amplitudes and then nonlinearly generate secondary smaller scale size ( $\sim 3$  m's) via the two-stream and/or gradient-drift instability mechanisms. Sharma [1989] has studied the gradient-drift instability in presence of an HF pump in the equatorial E-region case including the thermal nonlinearity. We present results for the high-latitude case below. However, first we present results of the calculation for the situation when the dominant nonlinearity is due to the ponderomotive force effects (weakly collisional case,  $v_e < |\omega_L|$ ) and when the nonlinear ohmic heating effects are neglected (the case considered by Lee et al. [1972]). The dispersion relation for the gradient drift instability in this case is given by

$$\omega(1 + \alpha) - k_{\perp} \cdot v_d + iD_{\perp} k_{\perp}^2 + i \hat{v}_{in} \hat{k}_o \omega = - \frac{2v_e |v_o|^2 k_{\perp}^2 \omega_p^2 \delta}{\Omega_e^2 (\delta^2 + v_e^2 \omega_o^2)} \quad (12')$$

where  $\hat{k}_o = \hat{e}_z \cdot (\hat{\epsilon}_n \times k_{\perp}) / k_{\perp}^2$

From (12'), one may readily calculate the real frequency,  $\omega_k$ , and growth rate,  $|\gamma|$ , by substituting  $\omega = \omega_r + i|\gamma|$  ( $|\gamma| < \omega_r$ ). This expressions is similar to the one obtained by Lee et al. [1972] and yields similar criteria for influencing the gradient-drift instability by the external pump wave, i.e., destabilization (stabilization) occurs when  $\delta < 0$ ,  $\omega_o <$

$\omega_{pe}$  ( $\delta > 0$ ,  $\omega_o > \omega_{pe}$ ). For the low latitude parameters,  $v_e \sim 4 \times 10^4 \text{ s}^{-1}$ ,  $v_{in} \sim 2.5 \times 10^3 \text{ s}^{-1}$ ,  $v_d \sim 10^4 \text{ cm s}^{-1}$ , and  $\lambda_{\perp} \sim 100 \text{ m}$ , the pump electric field required for influencing the gradient drift mode in the E-region is  $\sim 0.2 \text{ V/m}$ , a value on the same order of magnitude as that obtained by Lee et al. [1972].

For the collisional case ( $v_e > |\omega_L|$ ), appropriate for the E-region ionosphere, we need to include the ohmic heating nonlinearity. The dispersion relation in this case may be obtained from

$$\omega_L(1+\alpha) - k_{\perp} \cdot v_{d\perp} + (D_{\perp} k_{\perp}^2 + \gamma_L) = \frac{v_t^2 k_{\perp}^2 [\tilde{\omega}_L + i(\gamma_L + \eta)] (\hat{k}_o - i\hat{v}_e)}{\Omega_e (i\Theta_n + \frac{3}{2}\tilde{\omega}_L)} \quad (12)$$

From (12) the growth rate for the gradient-drift instability in the presence of an HF pump wave may be written as

$$\gamma = \frac{\hat{k}_o \hat{v}_i}{(1+\alpha)^2} \left( k_{\perp} \cdot v_{d\perp} + \frac{v_t^2 k_{\perp}^2 \hat{k}_o \eta}{\Omega_e \Theta_n} \right) - \frac{D_{\perp} k_{\perp}^2}{1+\alpha} \quad (12a)$$

where  $\gamma_L = \frac{\hat{k}_o \hat{v}_i}{(1+\alpha)^2} (k_{\perp} \cdot v_{d\perp})$ ;  $\hat{k}_o = \frac{\hat{e}_z \cdot (\epsilon_n \times k_{\perp})}{k_{\perp}^2}$

$$\eta = \frac{4v_e \omega_{pe}^2 |v_o|^2 \delta}{v_t^2 (\delta^2 + v_e^2 \omega_o^2)}$$

From (12), we find that the pump is destabilizing (stabilizing) when  $\delta < 0$ ,  $\omega_o < \omega_{pe}$  ( $\delta > 0$ ,  $\omega_o > \omega_{pe}$ ) (note that for these modes  $\tilde{\omega}_L < 0$  and for the linearly unstable situation,  $\hat{k}_o < 0$ ). The threshold pump field requirement for  $v_{d\perp} \sim 1 \times 10^4 \text{ cm s}^{-1}$ ,  $\lambda_{\perp} \sim 100 \text{ m}$ ,  $v_e \sim 4 \times 10^4 \text{ s}^{-1}$ ,  $v_{in} \sim 2.5 \times 10^3 \text{ s}^{-1}$ , etc., is  $15 \text{ mV/m}$ . This estimate, for the parameters mentioned, is applicable to both the high and low latitudes. We find that the threshold pump electric field in the E-region to influence the gradient drift mode is easily down by an order of magnitude (or more) in

the case when the nonlinear ohmic heating effects were included in the analysis (eq. 12), compared with the case when collisional effects were neglected and the nonlinearity was due to the ponderomotive force effects (eq. 12'). The stability theory here has used the local approximation in deriving the dispersion relation. This approach is valid when  $k_{\perp} L_N \gg 1$ . For scale sizes such that  $k_{\perp} L_N \leq 1$ , a nonlocal approach should be considered for the analysis. In the appendix, we consider the effects arising from such a treatment. For the medium scale size modes such that  $k_{\perp} L_N \geq 10^2$  ( $\lambda \sim 100$  m) the local theory estimates may be considered representative.

#### 4. UPPER E-REGION MODES

At higher E-region altitudes at high latitudes, the effect of parallel currents introduces the possibility of additional plasma modes. These modes are likely to be favored at altitudes  $\geq 110$  km. In this region decreasing ion-neutral collision frequency implies inclusion of ion magnetization effects ( $v_i \leq \Omega_i$ ). But, depending on the ambient conditions, the regions of occurrence for the lower E-region modes (two-stream instability and gradient-drift instability) and the upper E-region modes may often overlap.

##### (1) Ion Acoustic (IA) Mode

At altitudes above  $\geq 110$  km, nearly transverse propagating ion-acoustic modes may be driven unstable by a combination of parallel and perpendicular equilibrium electron drifts [Kaw, 1973; Chaturvedi et al., 1987b; Villian et al., 1987]. There are indications that some auroral backscatter radar observations may be interpreted as the ion-acoustic modes [Villian et al., 1987; Haldoupis et al., 1986]. The dispersion relation in this case may be obtained from

$$\omega^2 - k^2 c_s^2 + i\omega v_{in} + i \frac{k^2 c_s^2}{[D:k^2]} \tilde{\omega}_{eL} \approx i \frac{2}{3} \frac{k^2 c_s^2 \eta}{\tilde{\omega}_{eL}} \quad (13)$$

where  $[D:k^2] = (D_{\perp\perp} k_{\perp}^2 + D_{||} k_{||}^2)$ ;  $D_{||} = v_t^2 / v_e$ .

The criterion for instability in this case is as follows. For modes with  $\tilde{\omega}_{eL} < 0$  (the minimum condition for linear ion-acoustic instability), the pump is further destabilizing (stabilizing) for  $\delta < 0$ ,  $\omega_o < \omega_{pe}$  ( $\delta > 0$ ,  $\omega_o > \omega_{pe}$ ). For modes with  $\tilde{\omega}_{eL} > 0$  (linearly stable case), the reverse is true. The threshold pump field in this case, for  $v_i \sim 3.6 \times 10^2 \text{ s}^{-1}$ ,  $v_e \sim 5.3 \times 10^3 \text{ s}^{-1}$ ,  $T_e \sim 0.1 \text{ eV}$ ,  $v_t \sim 1.3 \times 10^7 \text{ cm s}^{-1}$ , etc., is 30 mV/m. A more precise determination of the threshold for the HF induced ion-acoustic instability may be obtained by using the kinetic ion equations so as to include the ion-Landau damping effects. The above estimate is a good approximation for scale sizes larger than the ion mean free path ( $> 1$  meter).

## (2) Electrostatic Ion Cyclotron (EIC) Mode

There is considerable speculation that at the upper E-region altitudes ( $\geq 130$  km), the generation of EIC modes by parallel currents may result in yet another type of auroral backscatter radar return [D'Angelo, 1973; Chaturvedi, 1976; Fejer et al., 1984; Satyanarayana et al., 1985; Providakes et al., 1985; Prikrýl et al., 1988; Villain et al., 1987]. This instability is favored at altitudes where  $v_i \ll \Omega_i$ . Chaturvedi et al. [1987a] and Laxmi and Tripathi [1988] have considered the possibility of HF-induced ion-cyclotron mode excitation but both these papers used the ponderomotive force nonlinearity. The nonlinear Joule heating of electrons may be the dominant coupling mechanism in this case also, as  $v_e > |\omega_L|$  is likely to be satisfied. The dispersion relation may be obtained from

$$\omega^2 - \Omega_i^2 - k^2 c_s^2 + i k^2 c_s^2 \left( \frac{\tilde{\omega}_{eL}}{[D:k^2]} \right) = i \frac{k^2 c_s^2 (\tilde{\omega}_{eL} + i\eta)}{(i \frac{3}{2} \tilde{\omega} - \Theta_n - \frac{[k^2:\kappa_e]}{n_o})} \quad (14)$$

where  $[k^2:\kappa_e] \equiv (k_{\perp}^2 \kappa_{e\perp} + k_{\parallel}^2 \kappa_{e\parallel})$



It may be noted that the form of pump-associated terms in the case of the EIC mode (eq. 14) is similar to the one in the ion-acoustic mode case (eq. 13). This is not surprising as the electron dynamics in the two cases are quite similar. The instability criterion for the HF-induced EIC mode is thus similar to the ion-acoustic mode case. But the occurrence of the EIC mode is likely at higher altitudes when  $\Omega_i \gg v_i$ ; whereas, the ion acoustic mode may be excited at lower altitudes, such that  $\Omega_i \lesssim v_{in}$ . The threshold pump field for the EIC instability, for  $v_{in} \sim 10 \text{ s}^{-1}$ , is  $\sim 5 \text{ mV/m}$ . Due to the neglect of ion temperature and the use of fluid equations for simplicity, the theory presented here has not considered the case of higher harmonics ( $\omega_n \sim n\Omega_i$ ). The use of ion kinetic equations ensures inclusion of these effects and ion-Landau damping effects [Chaturvedi et al., 1987a], and is planned for future work.

### (3) Current Convective Instability (CCI)

This instability, which occurs in the presence of a parallel current and a transverse density gradient, has been applied to the generation of high-latitude F-region irregularities in the intermediate scale size range ( $\sim 100 \text{ m's}$ ) [Ossakow and Chaturvedi, 1979]. In the lower E-region (100 - 115 km), the growth rate of the gradient drift instability is much larger than the current-convective instability [Chaturvedi and Ossakow, 1981], but at higher altitudes in the E-region ( $> 120 \text{ km}$ ) the current-convective instability may occur and generate longer scale size ( $> 100 \text{ m's}$ ) irregularities. The dispersion relation of the current-convective instability may be obtained from

$$(\tilde{\omega}_{eL} + i [D:k^2] \frac{v_t^2 k_\perp^2 k_o^2 (-i\tilde{\omega}_{eL} + \eta)}{\Omega_e (\theta_n - i \frac{3}{2} \tilde{\omega}_{eL})}) (i\tilde{v}_i + k_o) = (-i \frac{[D:k^2] \Omega_e}{v_t^2 k_\perp^2} + k_o) \omega_L \quad (15)$$

In absence of the pump wave, eq. (15) yields the familiar dispersion relation for the current-convective instability [Ossakow and Chaturvedi, 1979]. In this case,  $\theta_n > |\omega_L|$  and the criterion for HF induced destabilization (stabilization) for the current-convective instability is  $\delta < 0$ ,  $\omega_o < \omega_{pe}$  ( $\delta > 0$ ,  $\omega_o > \omega_{pe}$ ). The threshold pump field required in

this case, for  $v_e/\Omega_e \sim 10^{-4}$ ,  $k_{||}/k_{\perp} \sim (m_e/m_i)^{1/2}$ ,  $v_i/\Omega_i \sim 10^{-3}$ ,  $v_{d||} \sim 1 \times 10^5 \text{ cm s}^{-1}$ ,  $L_N \sim 5 \times 10^5 \text{ cm}$ ,  $E \sim 2 \text{ mV/m}$ . This instability is similar to the gradient drift instability and generates relatively longer scale size irregularities. The above analysis has been carried out using the local approximation which is valid for wavelengths satisfying,  $k_{\perp} L_N \gg 1$ . At longer wavelengths, such that  $k_{\perp} L_N \lesssim 1$ , non-local effects are important and have been considered in the appendix for the case of the gradient drift instability. For the scale sizes of interest ( $\lambda_{\perp} \sim 100 \text{ m}$ , for  $L_N \sim 5 \text{ km}$ ,  $k_{\perp} L_N \sim 10^2$ ), the local theory expression may be considered adequate.

## 5. DISCUSSION

In the above, we have described several low frequency plasma instabilities which may be influenced by the presence of a large amplitude HF pump in the high and low latitude E-region. There have been several artificial ionospheric modification (AIM) heating experiments resulting in the generation of small scale size plasma irregularities in the high latitude E-region. The various experimental observations are indicative of apparently a variety of processes occurring in this region during the ionospheric heating experiments [Stubbe and Kopka, 1983; Hibberd et al., 1983; Coster et al., 1985; Djuth et al., 1985; Hoeg et al., 1986]. Some features of these observations have been explained in terms of the well known plasma instability mechanisms associated with the HF pump wave such as the resonance instability [Vaskov and Gurevich, 1977; Inhester, 1982], and the thermal parametric instability [Grach et al., 1977; Das and Fejer, 1979; Dysthe et al., 1983]. Some aspects of the observations point towards a role that the natural plasma modes of this region may be playing. For instance, the observed radar backscatter spectra of the artificially-generated irregularities (AI) show similarities to that obtained in the case of natural irregularities, and, in some observations the effects seen associated with the artificially excited irregularities are similar to those in the case of the natural irregularities (e.g., enhanced heating). In the following, we discuss the E-region instabilities discussed in the previous sections in view of the previous and possible future ionospheric modification (heating) experiments.

(a) Two Stream Instability - This instability has been discussed in the context of ionospheric heating experiments at high latitudes by Hibberd et al. [1983] and Hoeg et al. [1986]. The linear instability, without the pump wave, requires that the ambient d.c. electric field be larger than  $\sim 20$  mV/m (i.e., the relative electron Hall drift be larger than the ion sound speed,  $\sim 350$  m/s). The Hall current peak is around  $\sim 110$  km altitude in the high-latitude E-region and this instability is favored around the region of peak current intensity. At higher altitudes, the relative drift between electrons and ions decreases as the ion magnetization effects (and the ion drift effects) increasingly assume importance. In regions where the ionosphere is stable to the linear two stream instability,, a contribution from another source of free energy may create conditions for the onset of the instability. In an ionospheric heating experiment, an HF pump wave may thus excite the two stream instability in the regions even where the current is linearly sub-threshold. In Hoeg et al. [1986], one set of modification experiment observations at higher E-region altitudes is described as two-stream-like at a time when the natural two stream instability was observed at lower altitudes. The threshold pump electric field required for the two stream instability is  $\sim 60$  mV/m which is on the order of the pump wave strength in these experiments in the E-region ( $>90$  mV/m). The natural type I irregularities have often been associated with enhanced electron temperatures in the high latitude E-region [Schlegel and St.-Maurice, 1981]. In the presence of the HF pump wave, the electron temperature is enhanced by an amount proportional to  $(m_n V_{eo}^2/3)$  where  $m_n$  is the mass of neutrals and  $V_{eo}$  is the electron quiver velocity. An artificial ionospheric modification (heating) experiment may be carried out to reproduce the phenomenon of increased  $T_e$  associated with the type I natural high-latitude E-region irregularities over the above mentioned enhancement. The growth times of the two-stream instability generated irregularities are on the order of  $\sim 0.1$  sec.

Furthermore there appear to have been no heating experiments at the low latitudes. An artificial excitation of type I modes during sub-threshold conditions and/or at altitudes away from the peak electrojet layer may aid in testing the two-stream instability interpretation of the natural type I echoes.

(b) Gradient Drift and Current-Convective Instabilities - The gradient drift instability may occur when the d.c. electric field is sub-threshold for the two-stream instability ( $< 20$  mV/m), requires a transverse density inhomogeneity, and has a growth time period on the order of  $\sim$  tens of secs. Hibberd et al. [1983] discarded the two-stream instability interpretation of their observations on account of the slow time period associated with the irregularities in their experiment ( $\sim 30$  sec), which was much larger than the two-stream instability--associated time scale of  $\sim 0.1$  sec. Later, for some other ionospheric modification experiments, the gradient drift instability had been considered as a possible mechanism [Djuth et al., 1985; Hoeg et al., 1986]. This instability linearly generates larger scale sizes ( $\sim 100$ 's m) which may grow to larger amplitudes and then nonlinearly generate the smaller scales via the two-step process [Sudan et al., 1973]. The pump wave threshold electric field required for the gradient-drift instability in the high-latitude E-region is  $\sim 15$  mV/m for an altitude  $\sim 110$  km and a d.c. electric field strength of  $\sim 10$  mV/m. Thus a combination of ambient d.c. electric field and pump wave of less than the peak strengths reported in the above mentioned modification heating experiments seems capable of readily exciting the gradient drift instability. At higher altitudes, the electrojet strength ebbs and larger pump wave strength may be required for the gradient drift mode excitation. But at high-latitudes, the presence of field-aligned currents (FAC) may result in a pump wave-induced gradient instability, the current-convective instability (CCI), even at higher altitudes (outside the electrojet region). The pump wave threshold for the current convective instability at  $\sim 150$  km is  $\geq 2$  mV/m where a presence of field aligned current of strength  $\sim 10 \mu\text{A/m}^2$  has been assumed. The current convective instability generates longer scale size irregularities ( $\sim 100$ 's m) and the associated growth periods are  $\sim 10$ 's secs. A cascade to smaller scale sizes via the two-step mechanism may then result in meter-scale irregularities detectable by a VHF radar. Thus in an ionospheric modification (heating) experiment, it may be possible to observe HF pump wave induced irregularities well above the electrojet region and still having slow growth time scales. The spectra of irregularities thus generated will be of type II if detected by a VHF backscatter radar.

A similar experiment may be carried out at low latitudes to artificially excite (or suppress) the type II irregularities at low latitudes. A generation of type II-like irregularities in the regions away from the electrojet layer may thus aid in testing the model of natural type II echoes in terms of the gradient drift instability and the two-step theory.

For the gradient drift instabilities, an important consideration at large wavelengths is the modification of the growth rate and the threshold criterion due to the non-local effects. The local theory approximation is generally valid when  $k_{\perp} L_N \gg 1$ . In the E-region, the gradient scale length,  $L_N \sim 6$  kms and for scale sizes of interest ( $\lambda_{\perp} \sim 100$ 's m),  $k_{\perp} L_N \sim 10^2$ , and thus the nonlocal effects may still be regarded as small. For smaller values of  $L_N$ , and/or for larger  $\lambda$ 's such that  $k_{\perp} L_N \sim 1$ , a nonlocal analysis is required. In this case ( $k_{\perp} L_N \sim 1$ ), the growth rates are reduced and larger pump thresholds are required.

(c) Ion Acoustic and Electrostatic Ion Cyclotron Modes - The observations of natural plasma irregularities in the high latitude E-region ionosphere have indicated a presence of apparently many types of plasma irregularities in contrast to the equatorial case where most of the observations have been interpreted in terms of the two-stream modes (type I radar spectra) and gradient drift modes (type II spectra). The irregularity classification of high latitude observations is still emerging, based on the VHF and HF backscatter radar spectra and in-situ rocket observations. The presence of low-frequency ion modes in association with the parallel currents at high latitudes has been considered as a possible interpretation of many E-region radar observations. For example, the EIC mode has been invoked by Fejer et al. [1984], Prikryl et al. [1988] and Villain et al. [1987] for some of their observations. Villain et al. [1987] have mentioned the ion acoustic mode for some of their observations. Thus it is expected that the ionospheric modification experiments at high latitudes will provide a richer variety of observed phenomena than expected at the lower altitudes.

In regions of the upper E-region electrojet layer, as mentioned earlier, the threshold condition for the excitation of the two stream instability may not be met because of ion magnetization effects. It has

been suggested that an obliquely propagating ion acoustic wave (with a finite parallel wave vector) will be unstable to a combination of transverse and parallel electron drifts [Chaturvedi et al., 1987b; Villain et al., 1987] and at higher altitudes the field-aligned currents will destabilize EIC modes [D'Angelo, 1973; Chaturvedi, 1976; Satyanarayana et al., 1985; Providakes et al., 1985]. In the ionospheric modification (heating) experiments, an artificial excitation of these modes is possible by means of the HF pump wave. For the upper electrojet regions where  $v_i \sim \Omega_i$ , the EIC mode is heavily damped due to ion-neutral collisional effects, but the excitation of the ion acoustic mode is possible. The threshold pump electric field required for the ion acoustic instability at  $\sim 120$  km altitude is  $\sim 30$  mV/m which is in the range of the artificial ionospheric modification (AIM) heating experiments mentioned above. At higher altitudes, the EIC mode could be excited artificially for similar threshold values. The EIC generation is also possible at F-region altitudes [Chaturvedi et al., 1987a].

Both the ion acoustic and EIC modes are obliquely propagating modes. The natural E-region irregularity radar observations at high latitudes have often detected returns at large aspect angles implying a finite parallel wavenumber associated with the irregularities. A signature of these modes would be a similar aspect angle dependence observed by radar detected artificial generated irregularities during ionospheric heating experiments in the upper E- and F-regions. Further, at higher altitudes, the nonlinearly developed EIC turbulence is expected to result in energetic ions (at 150 - 200 km) or possibly ions with non-thermal distributions (above 250 kms) [Satyanarayana et al., 1989]. Detection of super-thermal ions could be used as a possible diagnostic for the artificially induced electrostatic ion-cyclotron wave turbulence.

The generation of ion acoustic and EIC modes in the presence of a field aligned current is possible in both the overdense and underdense regions, depending on the altitude of the resonance layer. In the linearly stable situation, the underdense region is favored for the pump wave-induced instability ( $\omega_o > \omega_{pe}$ ). But in presence of a field aligned current, for the marginally stable or unstable conditions, an HF pump wave is further destabilizing to the ion acoustic and EIC instabilities in the overdense region ( $\omega_o < \omega_{pe}$ ). The time scale of growth for these modes is

< 1 sec. The mode excitation by this mechanism in the underdense and overdense regions may have some relevance to the observations of Hoeg et al. [1986].

## 6. SUMMARY

In conclusion, we have found that by using a high frequency pump wave at high latitude E region altitudes, the following observable effects may be induced in an artificial ionospheric modification experiment.

(i) For a situation when the electrojet strength is sub-threshold ( $v_{dl} < c_s$ ), or, in a situation when at the peak electrojet altitudes (at  $\sim 110$  km) the two stream instability may be operative ( $v_{dl} > c_s$ ) but at the same time at higher altitudes the relative electron drift may be sub-threshold due to the ion magnetization effects ( $|v_{el} - v_{il}| < c_s$ ), a pump wave electric field strength of  $\sim 60$  mV/m may excite small meter scale size irregularities, observable by a VHF backscatter radar (type I spectra) on a time scale of  $\sim 0.1$  sec. These irregularities are expected to result in enhanced electron temperatures in the region.

(ii) The pump wave electric field of strengths  $\sim 10$  mV/m could generate medium scale ( $\sim 100$ 's meters) irregularities on the time scales of  $\sim$  tens of seconds at the lower and upper E-region altitudes via the gradient drift and/or current-convective instabilities. These irregularities may then nonlinearly generate smaller scale sizes ( $\sim$  meters) via the two step mechanism. The small scale size irregularities are detectable via a VHF backscatter radar (type II spectra). The primary irregularities are also expected to result in the scintillations of RF signals.

(iii) The pump wave electric field strengths of  $\sim 10 - 30$  mV/m could directly generate small scale size ( $\sim$  meters) irregularities via the ion-acoustic instability in the altitude region 110-130 kms and via the electrostatic ion-cyclotron instability at altitudes  $\gtrsim 130$  km. The detection of these irregularities is possible by a VHF or HF backscatter radar. These modes have a finite parallel wave vector and a study of aspect angle dependence of radar returns could be used to reveal this

feature. At higher altitudes, as a consequence of the nonlinear development of the EIC instability, the detection of energetic ions would be a signature of these modes.

(iv) Similar experiments may be carried out at low latitudes also. These could include generation of irregularities (types I and II) in regions away from where the peak electrojet strength occurs (near 105km altitude). At altitudes separated from the peak electrojet layer, or, during sub-threshold electrojet strengths, an artificial excitation of type I irregularities will be a test of the two-stream instability model. Similarly, a generation of type II irregularities at altitudes separated from the main electrojet region will verify the gradient-drift instability and two-step theory models for equatorial electrojet irregularities. The strength of the pump electric field required in these cases is approximately 60mV/m and 15mV/m for generation of the type I-like and type II-like irregularities, respectively.

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## APPENDIX

### NONLOCAL $\underline{E} \times \underline{B}$ INSTABILITY IN THE E-REGION

In the E-region, there have been observations of long-wavelength irregularities, which have been associated with the electrojet Hall currents at both the equator [Kudeki et al. 1982, Pfaff et al. 1987] and at high-latitudes [Basu, 1988]. In this region, the observed wavelengths are  $> 1$  km while the driving density gradient scale size is in the range of  $\sim 6-10$  kms. Thus, typically, in the E-region, for the long wavelengths,  $kL_N \sim 10$ . It is therefore of interest to examine this instability with the nonlocal effects included at long-wavelengths in the presence of the pump wave.

In this section, we present a simple model calculation for the parametric instability of the GDI by an HF-pump to illustrate the importance of nonlocal effects on this instability. We consider a simplified density model

$$n_o(x) = \begin{cases} n_1 & x < 0 \\ n_2 & x > 0 \end{cases} \quad (A1)$$

As before the pump and the high frequency modes are assumed to be electrostatic. The simplified ion and electron equations are given as

$$n_{iL} = i \frac{e}{m_i v_i \omega_L} \nabla \cdot (n_o \nabla \phi_L) \quad (A2)$$

and

$$\frac{\tilde{\omega}_L}{n_o} \frac{\tilde{n}_{eL}}{\omega_L} + i \frac{v_{te}^2}{\omega_e} \nabla \left( \frac{T_{eL}}{T_{eo}} - \psi_L \right) \times \hat{e}_z \cdot \underline{\varepsilon}_n \approx 0 \quad (A3)$$

We have neglected the diffusion (and recombination) damping effects for simplicity here. We use eq. (9) in (A3) to arrive at

$$(\tilde{\omega}_L - \frac{v_{te}^2}{\Omega_e} k_y \epsilon_n \xi) \frac{n_{eL}}{n_0} = - \frac{v_{te}^2}{\Omega_e} (k_y \epsilon_n) \frac{e\phi_L}{T_{eo}} \quad (A4)$$

$$\xi = \frac{4v_e}{\Theta_n} \frac{|v_{eo}|^2}{v_{te}^2} \frac{\omega_p^2 \delta}{\delta^2 + v_e^2 \omega_0^2} = \frac{\eta}{\Theta_n} \quad (A5)$$

We have used the local approximation for the high-frequency side-bands in obtaining (A4). This has been done for analytical simplicity and may be a good approximation in the case of an ES pump such that  $k_0 > k_L$ . This enables one to obtain a differential equation from (A2) and (A4) which describes the nonlocal  $\underline{E} \times \underline{B}$  gradient-drift mode,

$$\frac{d}{dx} (n_0 \frac{d\phi_L}{dx}) - \frac{ik_y \frac{dn_0}{dx} \frac{v_i}{\Omega_i} \omega_L}{(\tilde{\omega}_L - \frac{v_{te}^2}{\Omega_e} k_y \xi \epsilon_n)} \phi_L = 0 \quad (A6)$$

We solve eq. (A6) by using the method described by Chandrasekhar [1961] for the Rayleigh-Taylor instability of a heavy fluid resting on top of a lighter fluid against acceleration. A similar analysis for the  $\underline{E} \times \underline{B}$  instability in F-region has been carried out by Huba and Zalesak [1983] without the HF pump wave effects. A solution for the potential  $\phi$  is assumed of form

$$\phi = \phi_1 e^{k_y x} + \phi_2 e^{-k_y x} \quad (A7)$$

For solutions satisfying the boundary conditions,  $\phi \rightarrow 0$  as  $|x| \rightarrow \pm \infty$ , we get

$$\begin{aligned}\phi &= \phi_1 e^{+k_y x} & x < 0 \\ \phi &= \phi_2 e^{-k_y x} & x > 0\end{aligned}\tag{A8}$$

Moreover, at  $x = 0$ , the potential is continuous, thus

$$\phi_1 = \phi_2\tag{A9}$$

Integrating Eq. (A6) across the boundary ( $x = 0$ ) and making use of (A7) - (A9), we obtain the nonlocal dispersion relation for the GDI in the E-region in the presence of a pump wave

$$\tilde{\omega}_L = i \frac{v_i}{\Omega_i} \left( \frac{n_1 - n_2}{n_1 + n_2} \right) \omega_L - \frac{k_y^2 v_{te}^2}{\Omega_e} \frac{(\xi_1 n_1 - \xi_2 n_2)}{(n_1 + n_2)}\tag{A10}$$

For the case,  $\theta_n > |\omega_L|$ , we find that the nonlocal growth rate is

$$\gamma_{NL}^E = \frac{v_i}{\Omega_i} \left( \frac{n_1 - n_2}{n_1 + n_2} \right) \left( k_y \cdot v_d - \frac{k_y^2 v_{te}^2}{\Omega_e} \frac{\xi_1 n_1 - \xi_2 n_2}{n_1 + n_2} \right)\tag{A11}$$

where subscript  $m$  ( $= 1, 2$ ) refers to the magnitude of quantities in the two regions.

We note from (A11) that the pump is destabilizing if  $\xi_1 < 0$  and  $|\xi_1 n_1| > |\xi_2 n_2|$ , which would roughly correspond to the earlier obtained criteria of  $\delta < 0$  in the local approximation. We note that  $(\delta_m)$  is a small number in only one region (because  $\omega_0$  is chosen to be resonant only in one region, say, region 1, with  $\omega_0 \approx \omega_{p1}$ ). Then, the pump is no longer resonant in the region 2 and therefore  $|\xi_1| \gg |\xi_2|$ . Thus, in this situation,  $|\xi_1 n_1| > |\xi_2 n_2|$  is satisfied. The local theory expression for the growth terms for the GDI in the presence of an HF pump wave (eq. 12a) may be obtained from (A11) by substituting  $L_N^{-1}$  for  $k_y((n_1 - n_2)/(n_1 + n_2))$

and using the approximation  $n_1 > n_2$ . Another consequence of the nonlocal theory is that at long wavelengths, the growth rate is proportional to the wavenumber  $k_y$  and thus the pump-induced contributions are smaller at larger scale sizes. Therefore, larger pump wave powers are required to achieve effects comparable to the case of small scale sizes. Thus, it is more difficult to influence the large-scale size interchange process than it is to influence the small-scale sizes by an external pump wave.

## REFERENCES

- Basu, Su., UV image, scintillation and radar study from Sondrestrom, Minutes of the HILAT/P. BEAR Science Team Meeting, Northwest Research Associates, Inc., Bellevue, WA, July 1988.
- Braginskii, S.I., Transport processes in a plasma, Reviews of Plasma Physics, Vol. 1, M.A. Leontovich, Ed., p. 205, Consultants Bureau, New York, 1965.
- Bujarbarua, S. and A. Sen, Artificial control of equatorial spread F, J. Atmos. Terr. Phys., 40, 615, 1978.
- Buneman, O., Excitation of field aligned sound waves by electron streams, Phys. Rev. Lett., 10, 285, 1963.
- Chandrasekhar, S., Hydrodynamic and Hydromagnetic Stability, p. 432, Oxford University Press, New York, 1961.
- Chaturvedi, P.K., Collisional ion cyclotron waves in the auroral ionosphere, J. Geophys. Res., 81, 6169, 1976.
- Chaturvedi, P.K. and S.L. Ossakow, The current convective instability as applied to the auroral ionosphere, J. Geophys. Res., 86, 4811, 1981.
- Chaturvedi, P.K., M.J. Keskinen and S.L. Ossakow, Production and control of ion-cyclotron instabilities in the high latitude ionosphere by high power radio waves, J. Atmos. Terr. Phys., 49, 57, 1987a.
- Chaturvedi, P.K., J.D. Huba, S.L. Ossakow, P. Satyanarayana and J.A. Fedder, Parallel current effects on two-stream electrojet plasma instabilities, J. Geophys. Res., 92, 8700, 1987b.
- Coster, A.J., F.T. Djuth, R.J. Jost and W.E. Gordon, The temporal evolution of 3-m striations in the modified ionosphere, J. Geophys. Res., 90, 2807, 1985.
- D'Angelo, N., Type 3 spectra of the radar aurora, J. Geophys. Res., 78, 3587, 1973.
- Das, A.C. and J.A. Fejer, Resonance instability of small-scale field-aligned irregularities, J. Geophys. Res., 84, 6701, 1979.
- Djuth, F.T., R.J. Jost, S.T. Noble, W.E. Gordon, P. Stubbe, H. Kopka, E. Nielsen, R. Bostrom, H. Derblom, A. Hedberg and B. Thide, Observations of E region irregularities generated at auroral latitudes by a high-power radio wave, J. Geophys. Res., 90, 12293, 1985.

- Dysthe, K.B., E. Mjølhus, H.L. Pecseli and K. Rypdal, A thermal oscillating two-stream instability, Phys. Fluids, 26, 146, 1983.
- Farley, D.T., A plasma instability resulting in field-aligned irregularities in the ionosphere, J. Geophys. Res., 68, 6083, 1963.
- Farley, D.T., and B.B. Balsley, Instabilities in the Equatorial Electrojet, J. Geophys. Res., 78, 227, 1973.
- Fejer, B.G., R.W. Reed, D.T. Farley, W.E. Swartz and M.C. Kelley, Ion cyclotron waves as a possible source of resonant auroral radar echoes, J. Geophys. Res., 89, 187, 1984.
- Fejer, J.A., Ionospheric modification and parametric instabilities, Rev. Geophys. Space Phys., 17, 135, 1979.
- Grach, S.M., A.N. Karashtin, N.A. Mityzkov, V.O. Rapoport and V. Yu. Trakhtengerts, Parametric interaction between electromagnetic radiation and ionospheric plasma, Radiophys. Quantum Electron. (Eng. Trans.), 20, 1254, 1977.
- Greenwald, R.A., Diffuse radar aurora and the gradient drift instability, J. Geophys. Res., 79, 4807, 1974.
- Gurevich, A.V., Nonlinear Phenomena In The Ionosphere, Springer-Verlag, New York, 1978.
- Haldoupis, C., G.J. Sofko, and J.A. Koehler, On ion-acoustic plasma waves at large magnetic aspect angles in the high-latitude E region of the ionosphere, J. Geophys. Res., 91, 5755, 1986.
- Hibberd, F.H., E. Nielsen, P. Stubbe, H. Kopka and M.T. Reitveld, Production of auroral zone E region irregularities by powerful HF heating, J. Geophys. Res., 88, 6347, 1983.
- Hoeg, P., E. Nielsen, P. Stubbe, and H. Kopka, Heater-induced 1 meter irregularities, J. Geophys. Res., 91, 11309, 1986.
- Hoh, F., Instability of Penning type discharges, Phys. Fluids, 6, 1184, 1963.
- Huba, J.D. and S.T. Zalesak, Long wavelength limit of the  $\underline{E} \times \underline{B}$  instability, J. Geophys. Res., 88, 10263, 1983.
- Inhester, B., Thermal modulation of the plasma density in ionospheric heating experiments, J. Atmos. Terr. Phys., 44, 1049, 1982.
- Kaw, P.K., Current driven ion wave instability in a weakly ionized collisional magnetoplasma, Phys. Lett., 44A, 427, 1973.

- Keskinen, M.J., P.K. Chaturvedi and S.L. Ossakow, Parametric excitation and suppression of convective plasma instabilities in the high-latitude F region ionosphere, J. Geophys. Res., 88, 7239, 1983.
- Kudeki, E., D.T. Farley, and B.G. Fejer, Long wavelength irregularities in the equatorial electrojet, Geophys. Res. Lett., 9, 684, 1982.
- Laxmi, V.N. and V.K. Tripathi, Radio wave heating and equatorial spread F, J. Atmos. Terr. Phys., 49, 1071, 1987.
- Laxmi, V.N., and V.K. Tripathi, Influence of HF radio waves on ion-cyclotron modes in the auroral ionosphere, J. Geophys. Res., 93
- Lee, K., P.K. Kaw and C.F. Kennel, External production and control of electrojet irregularities, J. Geophys. Res., 77, 4197, 1972.
- Ossakow, S.L., and P.K. Chaturvedi, Current convective instability in the diffuse aurora, Geophys. Res. Lett., 6, 332, 1979.
- Papadopoulos, K., K. Ko and V. Tripathi, Efficient parametric decay in dissipative media, Phys. Rev. Lett., 51, 463, 1983.
- Perkins, F., A theoretical model for short-scale field-aligned plasma density striations, Radio Sci., 9, 1065, 1974.
- Perkins, F.W., and J. Flick, Parametric instabilities in inhomogeneous plasmas, Phys. Fluids, 14, 2012, 1971.
- Perkins, F.W., and R.G. Roble, Ionospheric heating by radiowaves: Predictions for Arecibo and the satellite power station, J. Geophys. Res., 83, 1611, 1978.
- Pfaff, R.F., M.C. Kelley, E. Kudeki, B.G. Fejer, and K.D. Baker, Electric field and plasma density measurements in the strongly driven daytime equatorial electrojet, 2, The unstable layer and gradient drift waves, J. Geophys. Res., 92, 13578, 1987.
- Piliya, A.D., Wave conversion in a weakly inhomogeneous plasma, Sov. Phys. Tech. Phys. (Eng. Trans.), 11, 1567, 1967.
- Prikryl, P., D. André, G.J. Sofko, and J.A. Koehler, Doppler radar observations of harmonics of electrostatic ion cyclotron waves in the auroral ionosphere, J. Geophys. Res., 93, 7409, 1988.
- Providakes, J., D.T. Farley, W.E. Swartz, and D. Riggan, Plasma irregularities associated with a morning discrete auroral arc: Radar interferometer observations and theory, J. Geophys. Res., 90, 7513, 1985.

- Rogister, A. and N. D'Angelo, Type II irregularities in the equatorial electrojet, J. Geophys. Res., 75, 3879, 1970.
- Satyanarayana, P., P.K. Chaturvedi, M.J. Keskinen, J.D. Huba and S.L. Ossakow, Theory of the current-driven ion cyclotron instability in the bottom side ionosphere, J. Geophys. Res., 90, 12209, 1985.
- Satyanarayana, P., M.J. Keskinen, P.K. Chaturvedi and S.L. Ossakow, Effects of ion collisions on quasi-linear heating by the current-driven ion cyclotron instability in the high latitude ionosphere, J. Geophys. Res., 94, 5510, 1989.
- Schlegel, K. and J.P. St.-Maurice, Anomalous heating of the polar E region by unstable plasma waves, 1. observations, J. Geophys. Res., 86, 1447, 1981.
- Schlegel, K. and J.P. St.-Maurice, Short wavelength gradient-drift waves at high latitudes, Ann. Geophys., 1, 259, 1983.
- Schlegel, K., M. Rietveld and A. Maul, A modification event of the auroral E region as studied with EISCAT and other diagnostics, Radio Sci., 22, 1063, 1987.
- Sharma, A.K., Effect of RF on type II electrojet instability, J. Geophys. Res., 94, 3805, 1989.
- Simon, A., Instability of a partially ionized plasma in crossed electric and magnetic fields, Phys. Fluids, 6, 382, 1963.
- Stenflo, L., Stimulated scattering by collisional modes in the ionosphere, Radio Sci., 18, 1379, 1983.
- Stenflo, L., Parametric excitation of collisional modes in the high-latitude ionosphere, J. Geophys. Res., 90, 5355, 1985.
- Stubbe, P. and H. Kopka, Summary of results obtained with the Tromso heating facility, Radio Sci., 18, 831, 1983.
- Sudan, R.N., J. Akinrimisi and D.T. Farley, Generation of small-scale irregularities in the equatorial electrojet, J. Geophys. Res., 78, 240, 1973.
- Vaskov, V.V., and A.V. G' evich, Resonance instability of small-scale plasma perturbations, Sov. Phys. JETP, 46, 487, 1977.
- Villain, J.P., R.A. Greenwald, K.B. Baker and J.M. Ruohoniemi, HF radar observations of E region plasma irregularities produced by oblique electron streaming, J. Geophys. Res., 92, 12327, 1987.



Wagner, L.S., J.A. Goldstein, R.W. Lind, A.Y. Wong and M.J. McCarrick,  
Channel probe observations of the auroral ionosphere during HIPAS  
heating experiments, to appear in Radio Science, 25, 1990.  
Weatherall, J.C., M.V. Goldman and D.R. Nicholson, Parametric instabilities  
in weakly magnetized plasmas, Ap. J., 246, 306, 1981.

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